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Double Sheath Associated with Negative Ion Extraction from a Plasma Containing Negative Ions

H. Amemiya and G. Fuchs*

The Institute of Physical and Chemical Research, Hirosawa, Wako, Saitama-Pref. Japan 351-0198
*Institut für Plasmaphysik, Association EURATOM-FZJ, Jülich 52425, Germany

The double sheaths formed by plasmas that contain thermal electrons, as well as positive and negative ions has been investigated. The negative ion beam that can be extracted under these conditions is given as a function of the electric potential, the density ratio and the Langmuir limit. The result is useful when it comes to extract ion beams from negative ion sources.

1. Introduction

Double sheaths set up by electron emission [1] and a counter–stream [2] can be tailored to give optimum extraction of beams with regard to the Langmuir limit. Double sheaths containing negative ions are scarce [3]. In a previous work the effect of negative ions within a plasma upon electron beam extraction has been investigated [4]. This paper deals with double sheaths whereby the plasmas on both sides do contain negative ions. This is of practical interest if one wants to optimize negative ion beams from an NBI source.

2. Model

Consider a double layer formed by two plasmas, both containing negative ions. From the lower potential side (potential V=0), thermal electrons and negative ions flow with current density J_e and J_n. Particle densities $n_{e1}(V)$, $n_{n1}(V)$ are given by

$$n_{e1}=\frac{J_e}{e\sqrt{2e(V+V_e)/m}},\ n_{n1}\frac{J_n}{e\sqrt{2e(V+V_n)/M_n}},\quad (1)$$

where V_e and V_n are the potentials equivalent to the initial energy, m, M_p, M_n, are electron, positive and negative ion masses. Positive ions get reflected and their density $n_{p1}(V)$ within the sheath is

$$n_{p1}(V)=N_{p1}\exp(-eV/\kappa T_p),\quad (2)$$

where N_{p1} is the boundary value. From the high plasma potential side (V=V_a) positive ions flow with current density J_p, such that the density becomes

$$n_{p2}(V)=J_p/e\sqrt{2e(V_a-V+V_o)/M_p}\ ,\quad (3)$$

whereby the initial velocity is given by v_o according eV_o= $M_p v_o^2/2$. Electrons and negative ions are reflected. Their densities are

$$n_{e2}=N_{e2}\exp[-e(V_a-V)/\kappa T_e],$$
$$n_{n2}=N_{n2}\exp[-e(V_a-V)/\kappa T_n],\quad (4)$$

where T_e, T_n, T_p, are the temperatures and N_{e2}, N_{p2}, N_{n2} are the densities at the boundary.

3. Formulation

The right hand side of Poisson's equation is

$$N(V)/\varepsilon_o=-n_{e1}-n_{n1}+n_{p1}-n_{e2}-n_{n2}+n_{p2}\ ,\quad (5)$$

where ε_o is the dielectric constant in vacuum.

Introducing the following normalization, ξ=x/λ_D ,λ_D=$(\varepsilon_o\kappa T_e/N_{p1}e^2)^{1/2}$, η=$eV/\kappa T_e$, η_e= $eV_e/\kappa T_e$, η_n=$eV_n/\kappa T_e$, ν_{e1}=N_{e1}/N_{p1}, ν_{n1}=N_{n1}/N_{p1}, ν_{e2}=N_{e2}/N_{p2}, ν_{n2}=N_{n2}/N_{p2}, q=N_{p2}/N_{p1}, γ_n=T_e/T_n, γ_p=T_e/T_p, j_e=J_e/J_o, j_n=$J_n\sigma_n/J_o$, j_p=$J_p\sigma_p/J_o$, where σ_n=$(M_n/m)^{1/2}$, σ_p= $(M_p/m)^{1/2}$, J_o=$N_{p1}e(2\kappa T_e/m)^{1/2}$, Poisson's equation now reads

$$d^2\eta/d\xi^2=-e\rho/\varepsilon_o\ ,\ \rho=N/N_{p1}\quad (6)$$

$$\rho=-\frac{j_e}{\sqrt{\eta+\eta_e}}-\frac{j_n}{\sqrt{\eta+\eta_n}}+\exp(-\gamma_p\eta)+\frac{j_p}{\sqrt{\eta_a-\eta+\eta_o}}$$
$$-q\nu_{e2}\exp[-(\eta_a-\eta)]-q\nu_{n2}\exp[-\gamma_n(\eta_a-\eta)],\quad (7)$$

and the conditions at the plasma boundaries are

1) Quasi neutrality : ρ=0 at η=0, η_a.
2) Zero derivative of space charge density $d\rho/d\xi$=0 at η=0, η_a.
3) Zero electric field: $d\eta/d\xi$=0 at η=0, η_a.

Multiplying $d\eta/d\xi$ on both sides of (6) and integrating, we obtain the stress $(d\eta/d\xi)^2/2$, which automatically satisfies the condition $d\eta/d\xi$=0 at η=η_a. At η=0, then we obtain

$$0=2j_e(\eta_e^{1/2}-\sqrt{\eta_a+\eta_e})+2j_n(\eta_n^{1/2}-\sqrt{\eta_a+\eta_n})$$
$$+[1-\exp(-\gamma_p\eta_a)]/\gamma_p+2j_p(\sqrt{\eta_a+\eta_o}-\sqrt{\eta_o})$$
$$+q\nu_{e2}\{\exp(-\eta_a)-1\}+q\nu_{n2}\{\exp(-\gamma_n\eta_a)-1\}/\gamma_n\ .\quad (8)$$

The double layer does form, if eqn.(8) together with the boundary conditions is satisfied.

4. Double sheath with high potential

Putting $\exp(-\eta_a)$<<1, $\exp(-\gamma_p\eta_a)$<<1, $\exp(-\gamma_e\eta_a)$ <<1 and $\exp(-\gamma_n\eta_a)$<<1 and η_e=η_n, we get

$$\frac{j_e+j_n}{\eta_e^{1/2}}=1+\frac{j_p}{\sqrt{\eta_a+\eta_o}},\quad (9)$$

$$\frac{j_e+j_n}{\sqrt{\eta_a+\eta_e}} = \frac{j_p}{\sqrt{\eta_o}} - q(v_{e2}+v_{n2}), \quad (10)$$

$$\frac{j_e+j_n}{2\eta_e^{3/2}} - \gamma_p + \frac{j_p}{2(\eta_a+\eta_o)^{3/2}} = 0, \quad (11)$$

$$\frac{j_e+j_n}{2(\eta_a+\eta_e)^{3/2}} + \frac{j_p}{2\eta_o^{3/2}} = q(v_{e2}+\gamma_n v_{n2}), \quad (12)$$

$$\eta_e = \eta_n = \frac{1+j_p/(\eta_a+\eta_o)^{1/2}}{2\gamma_p - j_p/(\eta_a+\eta_o)^{3/2}}, \quad (13)$$

$$\eta_o = \frac{q(v_{e2}+v_{n2})+(j_e+j_n)/\eta_a^{1/2}}{2q(v_{e2}+\gamma_n v_{n2})-(j_e+j_n)/\eta_a^{3/2}}. \quad (14)$$

η_n and η_o given by (13) and (14) correspond to the Bohm criterion determining the ion fluxes. η_e (or η_n) increases from $1/(2\gamma_p)$ as η_a is decreased or j_p is increased. η_o increases from $1/(2\gamma_n)$ for the negative ion-rich plasma as η_a is decreased or j_e and j_n are increased. η_o tends to 1/2 of the simple sheath if $j_e=j_n=0$ and $\eta_a>>1$.

From (8), we obtain the Langmuir limit as

$$(j_e+j_n)(\sqrt{\eta_a+\eta_n}-\sqrt{\eta_n}) - j_p(\sqrt{\eta_a+\eta_o}-\sqrt{\eta_o})$$
$$= 1/\gamma_p - q(v_{e2}+v_{n2}/\gamma_n). \quad (15)$$

If η_a is extremely large, the limit is modified as

$$j_e + j_n \cong j_p. \quad (16)$$

Without j_n, we recover $J_e=(M_p/m)^{1/2}J_p$. Without j_p, we obtain $J_n=(M_p/M_n)^{1/2}J_p$, i.e. the negative ion beam is governed by the positive ion beam, and determined by the square root of the mass ratio.

5. Calculations and Results

We have five equations to determine the unknowns η_o, η_e, $j_e+j_n=j_{en}$, j_p and q from the known values η_a, v_{e2}, v_{n2}, γ_n and γ_p. We define $j_{en}=j_e+j_n$. This nonlinear system has been solved by

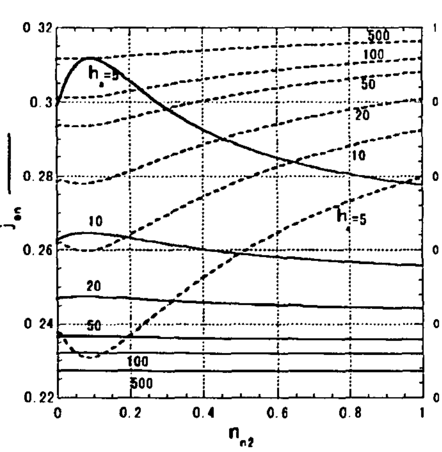
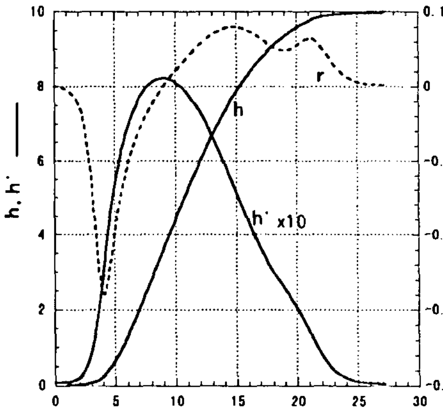


Fig. 1. j_{en} and j_{en}/j_p vs v_{n2} for $\eta_a=10$ and $v_{e2}=0.3$.

iteration starting with $\eta_o=1/2$, $\eta_n=1/(2\gamma)$ to get j_{en}, j_p and q. Afterwards new values for η_o and η_n, e.t.c were determined.

In Fig.1 for $\eta_a=10$, $\gamma_n=\gamma_p=10$, the beam density j_{en} has a maximum at a v_{n2} while η_a is small but becomes almost constant for higher η_a. This behavior holds in a wide range.

Fig. 2. η, η' and ρ vs ξ for $\eta_a=10$, $\gamma_n=\gamma_p=10$.



In Fig. 2 showing the profile of the double sheath, ρ is not symmetric as in the beam-free case, showing a narrow dip near the low potential side and a small bump on the higher side, though it was confirmed that the integral of ρ over the entire region is 0. For $v_{n2}=0.1$, η shows a wavy structure near η_a, suggesting a triple layer. As v_{n2} is increased above 0.1, η, η' and ρ resemble those of $v_{n2}=0$. Therefore, except the cases with a triple layer, the sheath thickness δ (normalized by λ_D) can be defined by the distance between $0.01\eta_a$ and $0.99\eta_a$. δ deviates from $\eta^{4/3}/j_{en}^{1/2}$, as η_a is decreased.

6. Conclusion

The double sheath theory has been extended to the case when a beam of negatively charged ions is extracted from a plasma containing such particles. Results are presented for the current densities of positively and negatively charged species, profiles of space charge, electric field and potential within the sheath. The potentials at the sheath edge will help to better understand the extraction of negative ions from negative ion sources.

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